GENTHERM

Thermoelectric Waste Heat Recovery Program for Passenger Vehicles

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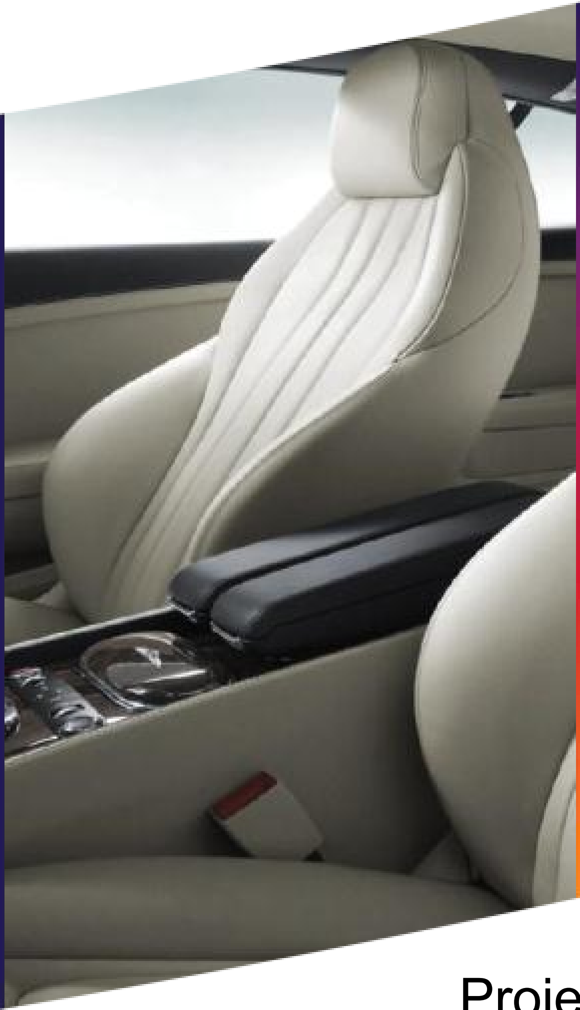
Gentherm Inc.

05/17/13



INSPIRING EFFICIENCY

Project ID # ACE080

GENTHERM PROGRAM OVERVIEW

Timeline

- Project start date: Oct. ‘11
- Project end date: Sept. ‘15
- Percent complete: 30%

Budget

- Total project funding: $15,794,813
  - DOE share: $9,553,950
  - Contractor share: $6,240,683 (40%)
- Funding received in FY11: $97,974
- Funding received in FY12: $1,688,898
- Funding for FY13: $3,711,630

Barriers

- Economic manufacture of TE materials and engines and TEG subsystem
- Environmental withstanding and robustness
- Vehicle level integration

Partners

- Interactions/collaborations
  - OEM Partners: BMW & Ford
  - Tier 1 Partner: Tenneco
  - University/Fed’l Partners: Caltech, NREL
- Project lead: Gentherm (formerly BSST/Amerigon)

Project objectives:

- A detailed production cost analysis for volumes of 100,000 units per year and a discussion of how costs will be reduced in manufacturing.
- A five (5) percent fuel economy improvement by direct conversion of engine waste heat to useful electric power for light-duty vehicle application. For light duty passenger vehicles, the fuel economy improvement must be measured over the US06 cycle.
- Confirmatory testing of the hardware to verify its performance in terms of fuel economy improvement.
- Scale up the TEG designed for passenger vehicles from 500W to 1kW-2kW for the Bradley Fighting Vehicle (TARDEC).

OBJECTIVES/RELEVANCE – MARCH '12–MARCH '13

Evaluate and redesign TEG device architecture to satisfy technical and economic goals

Define vehicle/platform that will provide best path towards a cost-effective system at 100,000 units per year

Start TEG engine scale-up and manufacturing cost-reduction activities

Design, build, test initial prototype TEG engines and start to assess TEG level packaging and design robustness solutions

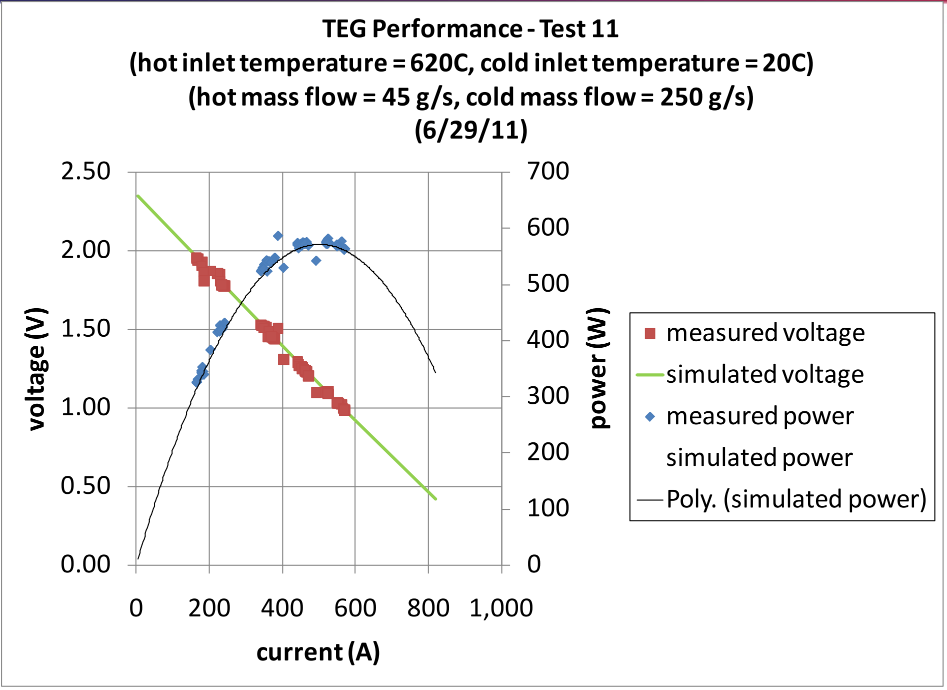
GENTHERM 2012/2013 PROGRAM MILESTONES

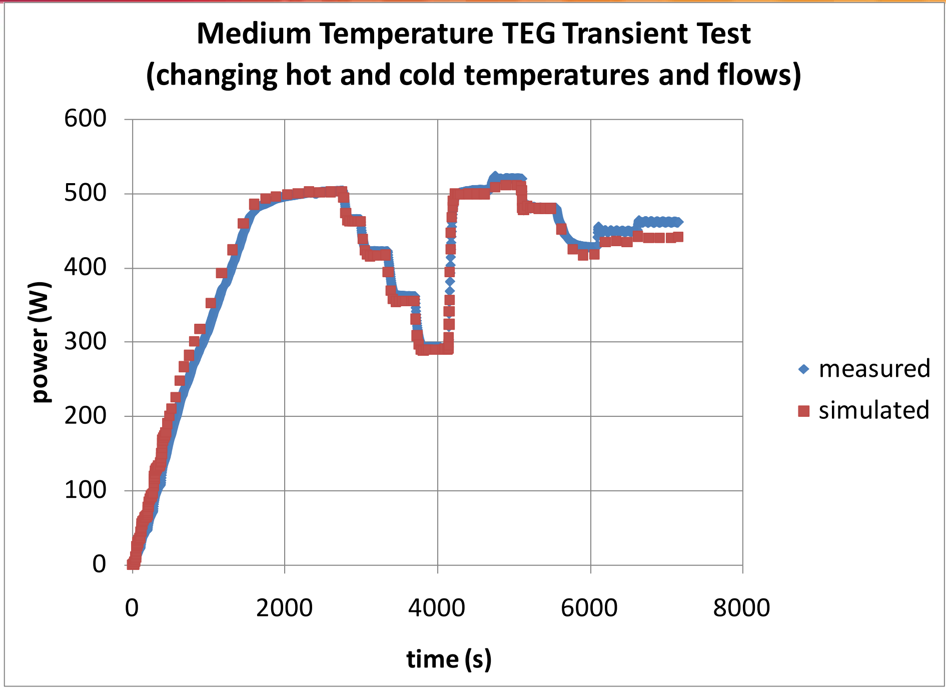
Month / Year	Subtask	Description	Status
Aug-12	1.1.1	Vehicle platform selected, vehicle performance baseline established including requirements for 5% FE gain	Completed
Aug-12	1.1.2	TEG system requirements defined, underfloor exhaust system boundary conditions, working fluid mass flows and packaging constraints documented.	Completed
Jun-12	1.1.8	Select TEG and TEG subsystem architectures	Completed
Jun-12	1.2.3	Develop initial encapsulation and sublimation suppression process concepts.	Completed
Feb-13		Initial TARDEC vehicle architecture/performance estimated	Completed
Mar-13		Cartridge test at TARDEC lab	On schedule
Sep-13	2.3	Improve SKU performance	On schedule
Sep-13	2.4	TE material sealing (encapsulation and sublimation control) developed	On schedule
Dec-13		TARDEC TEG system mock-up	On schedule

APPROACH - IMPROVE COST-EFFECTIVENESS OF TEG DESIGN

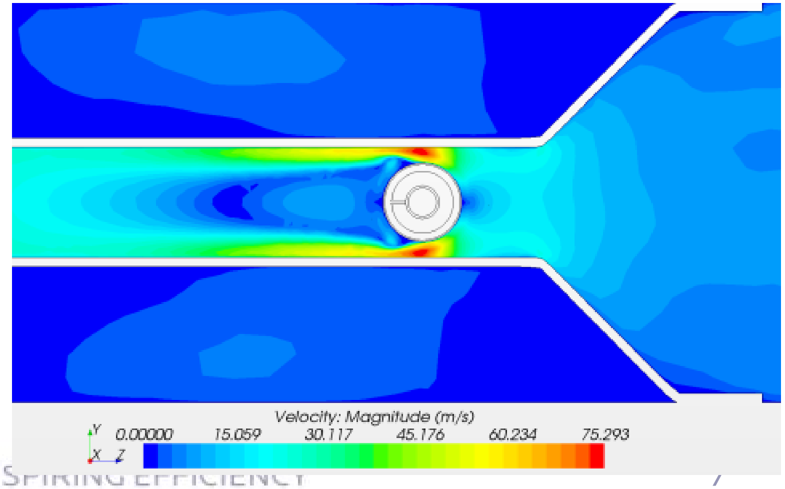
Attribute	2011: Proof of Concept	2012: Cartridge design
Construction	Single integrated unit	Modular, scalable
By-pass	Integrated, structural	External, optional
Current-voltage spec	~500 A, 1 V	~50A, 12-14 V
Scalability	Difficult, costly to modify	Adaptable building block-approach
Manufacturing	Complex, many parts	Modular, simplified manufacturing

APPROACH – USE MODELING (1D AND 3D) AND EXPERIMENTATION TO OPTIMIZE DESIGN





Gas flow analysis over single cartridge



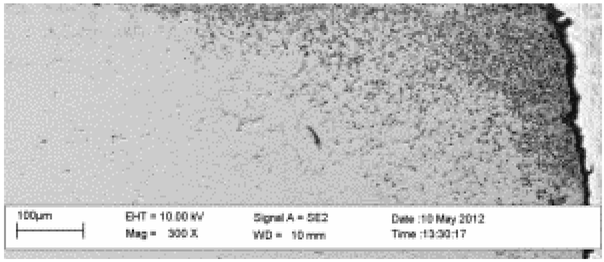
Use combination of experimentation and 1D and 3D modeling across project partners to understand design choices and optimize system design.

APPROACH – PROTECT DEVICE FROM SUBLIMATION/OXIDATION DEGRADATION

Primary functions

Provide Sb sublimation suppression in order to increase life span of TE device by reducing material erosion.

Prevent deposition of Sb on the device electrodes.

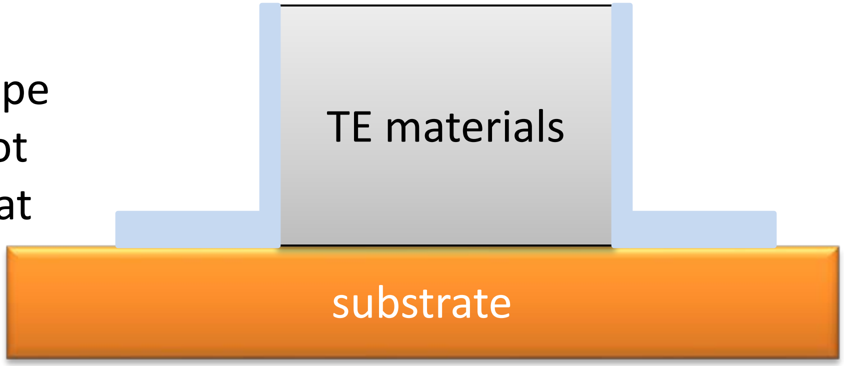


Example of sublimation driven erosion

Secondary functions

- Reduce thermal losses (convective and radiation) in the TE material
- Hermetically seal TE materials and other components of cartridge in order to prevent oxidation at operating temperatures

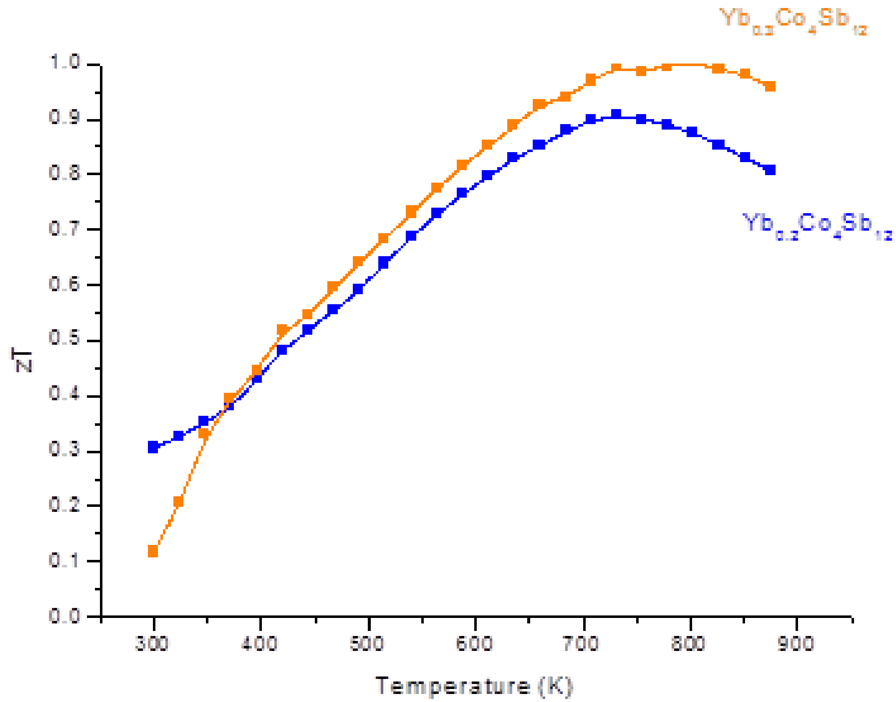
Selected coating must conform to shape of both TE materials and substrate (hot shunt) at operating temperature and at the storage temperature.



Objective: Improve properties of Skutterudite based materials

Method: map transport parameters and identify those that can be manipulated (i.e. Density of State manipulation)

Status: Comprehensive literature survey and good initial progress in repeating state of the art performances.



APPROACH – DEVELOP NOVEL MANUFACTURING METHODS FOR COST-EFFECTIVE SCALE UP

- Develop methods to combine manufacturing steps.
- Understand cost vs. performance tradeoffs.
- Net shape manufacturing to reduce material loss.
- Reduce number of parts.
- TE materials, engines and cartridges manufactured in California, USA.

ACCOMPLISHMENT – PROTECT DEVICE FROM SUBLIMATION/OXIDATION DEGRADATION

Broad search – large number of coatings are evaluated for cost and adhesion properties.

Macroscopic evaluation of coatings at room temperature and after exposure to 600C for several days.

Evaluations will continue with a narrowed list of candidate coatings.

Enamel

- ✓ Good adhesion to SKU
- ✓ Good hermeticity even at elevated temperature
- ✓ Poor CTE match with copper substrate

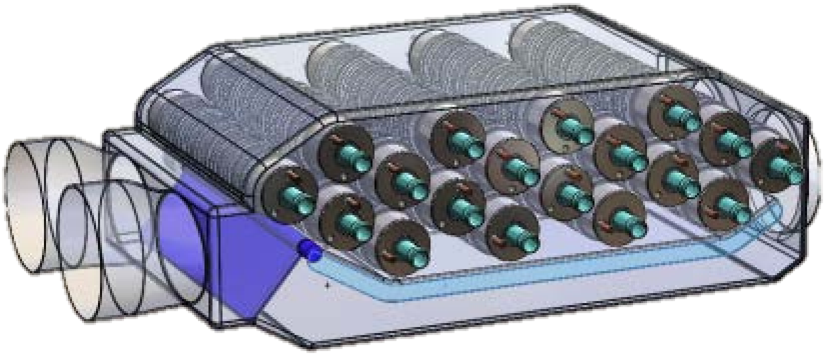
Alumina –Titania coating

- ✓ Good adhesion at room temperature
- ✓ Fracture of coating at elevated temperature on the stress concentration points (sharp edges).

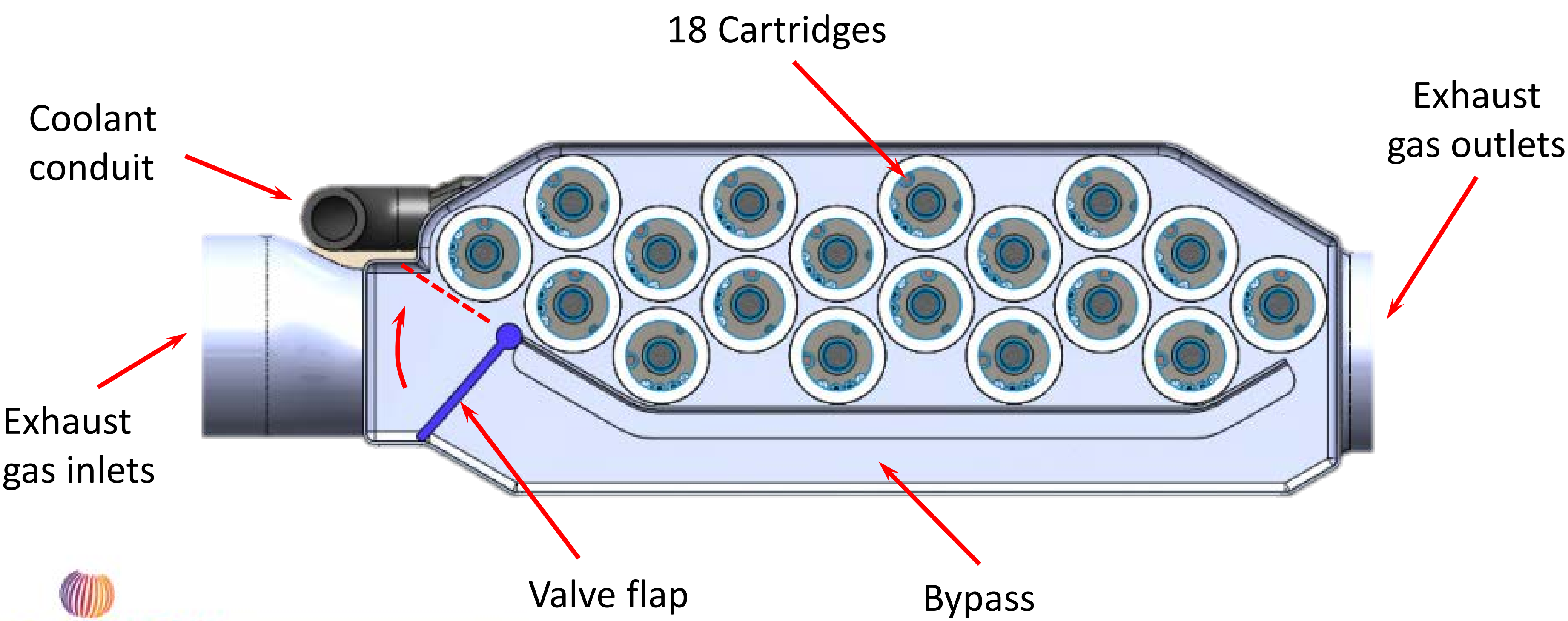
Alumina coating

- ✓ Plasma sprayed alumina on a Cu-SKU substrate.
- ✓ Provides good adhesion to both materials at room temperature.
- ✓ Currently being thermally cycled.

ACCOMPLISHMENT - TEG COMPONENT (CARTRIDGE) AND TEG ARCHITECTURE CONCEPT DEFINED



TEG building block (cartridge) defined and extrapolated to TEG design concept.



ACCOMPLISHMENT – VEHICLE PLATFORM/POWERTRAIN SELECTED

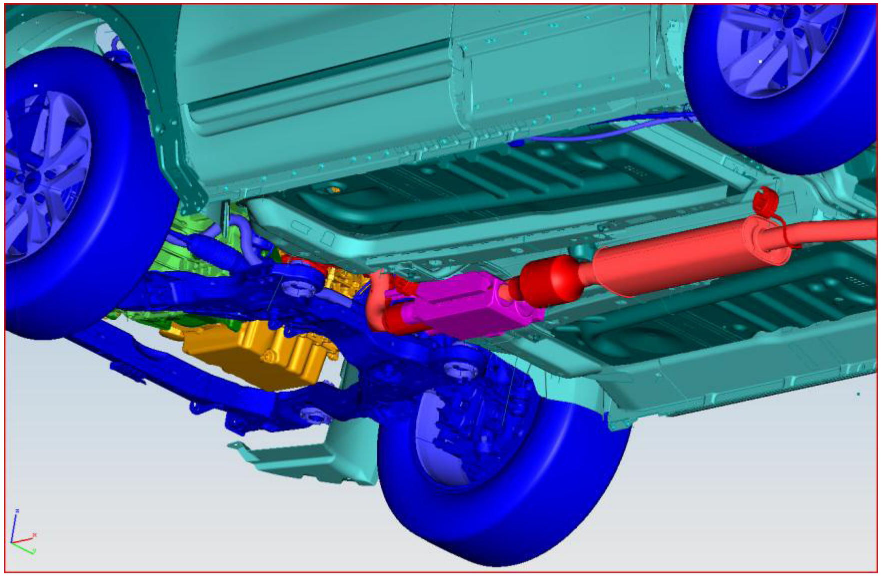
Vehicle platform/powertrain selections made by BMW and Ford after extensive trade-off analysis.

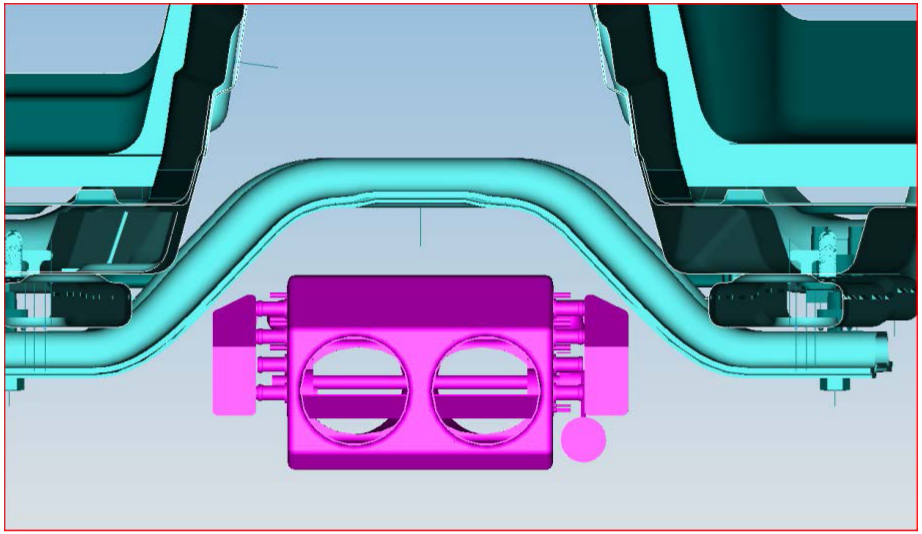
Selection allows the requirements for the TEG system(s) to be defined and the TEG design to be optimized against these vehicle requirements, operating conditions and economic factors.

Ford Explorer

BMW X3

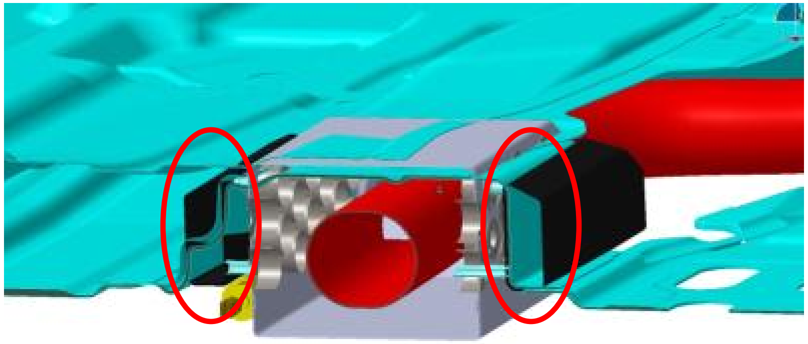
ACCOMPLISHMENT – INITIAL PACKAGING STUDY HAS BEGUN



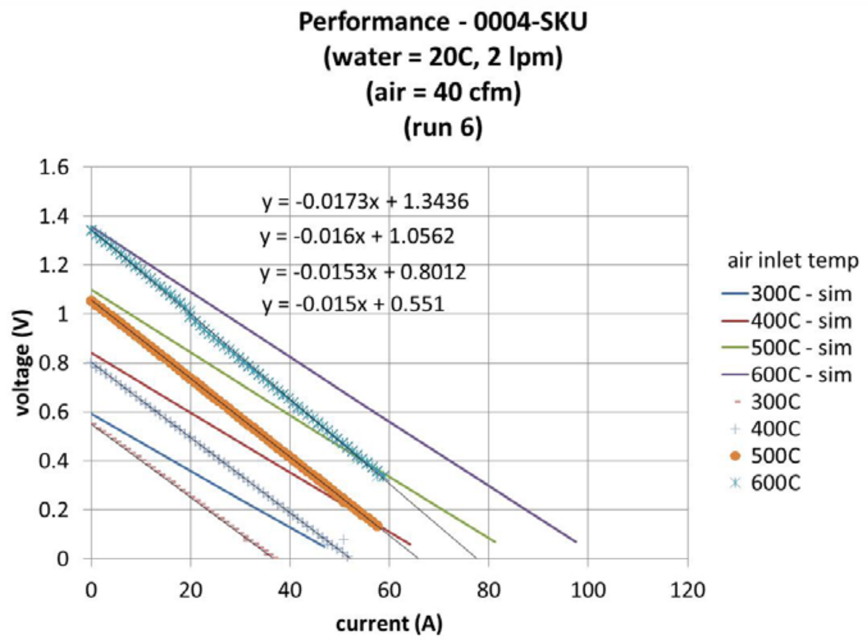


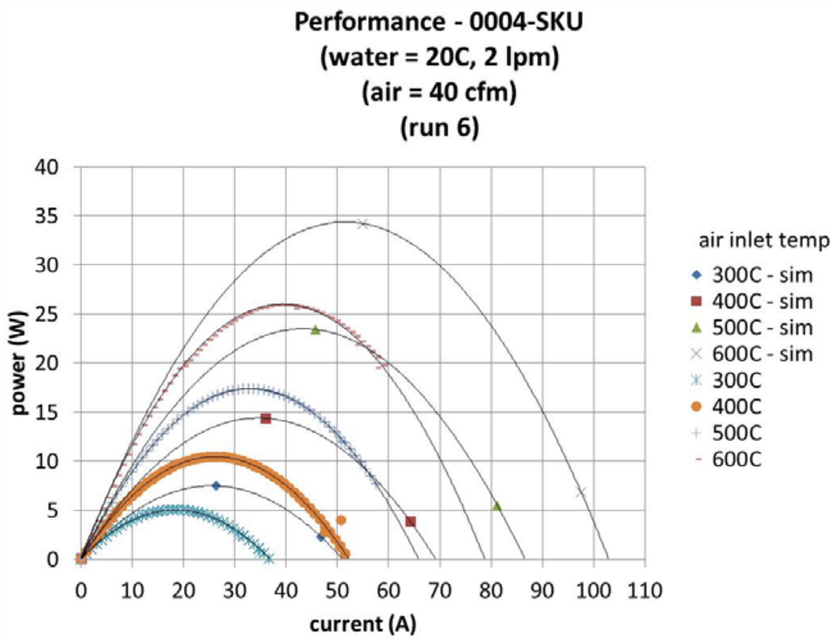
OEMs and Tier 1 have started to investigate the TEG design concept within the vehicle available package space.

This analysis provides critical information for the TEG design optimization space.



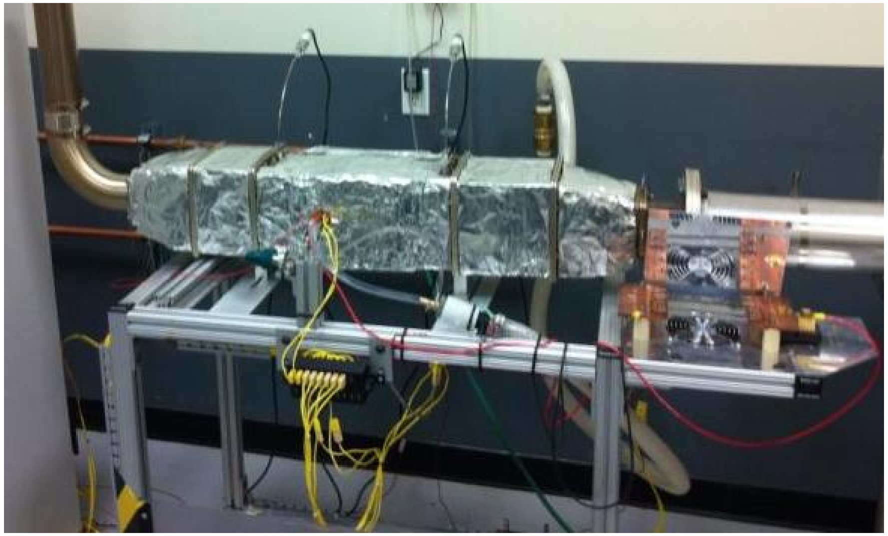
ACCOMPLISHMENT - INITIAL SKU CARTRIDGE RESULTS





Initial TEG building block (cartridge) made of SKU TE material has been built and tested. Initial test results are shown against expected performance.

Initial performance results show room for improvement against expected performance.



COLLABORATIONS

OEM leadership, including vehicle platform and powertrain definition and requirements, is provided by BMW and Ford.

Tier 1 support in the design of the “canning” of the TEG engines (cartridges) and integration into the vehicle exhaust systems is provided by Tenneco.

TE material improvement through extensive modeling and experiment is provided by Caltech.

TEG-level and vehicle-level performance will be confirmed by NREL (TEG test experience with cylindrical design).

FUTURE WORK

Further modeling and optimization, including 1D (MATLAB/Simulink) and 3D (CFD/FEA), will continue to achieve a design freeze

Component, cartridge, and multi-cartridge-level testing to continue, both for performance and durability

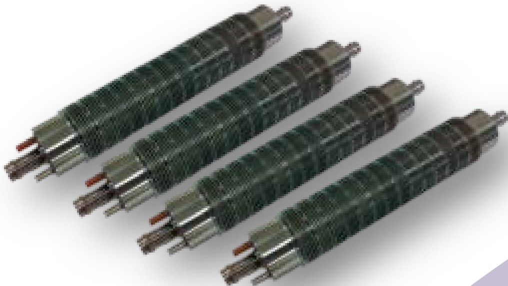
Vehicle and TEG system requirements to be completed, with significant input from new partner, Tenneco

Further work on oxidation/sublimation suppression coating

Further development of the TE material model for SKU from Caltech

Scale up TE material and cartridge fabrication methods, including tooling and process development, for commercialization quantities

FUTURE WORK - DOE PROGRAM SCHEDULE



Q3’12
1st cartridge
build and test

Q2’13
2nd cartridge build
and test

Q2’14
BMW, Ford, TARDEC
cartridges build

Q1’15
TEG vehicle installation
BMW, Ford, TARDEC

TARDEC (Tank Advanced Research and Development Engineering Command): TEG for Bradley Fighting Vehicle, 15 liter truck engine

SUMMARY

Cost-effective cartridge-based TEG design architecture has been conceptualized that will help achieve commercialization goals.

- Initial cartridges modeled, built and tested.
- Novel manufacturing techniques are being developed to further enhance the cost-effectiveness of the design at production quantities.

Vehicle platform/powertrain selections made by BMW and Ford after extensive trade-off analysis.

- Packaging study and requirements definition are being completed.

1D and 3D modeling build off of the successful modeling of the previous program to aid in TEG device and system optimization.

SKU TE material improvement analysis has begun at Caltech.

Early tests of oxidation/sublimation suppression coating systems show potential success.

ACKNOWLEDGEMENTS

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Tenneco: Bernd Scherer, Marcel Womann, Michael Miersch, Adam Kotrba

Caltech: Jeff Snyder, Yinglu Tang

NREL: John Rugh

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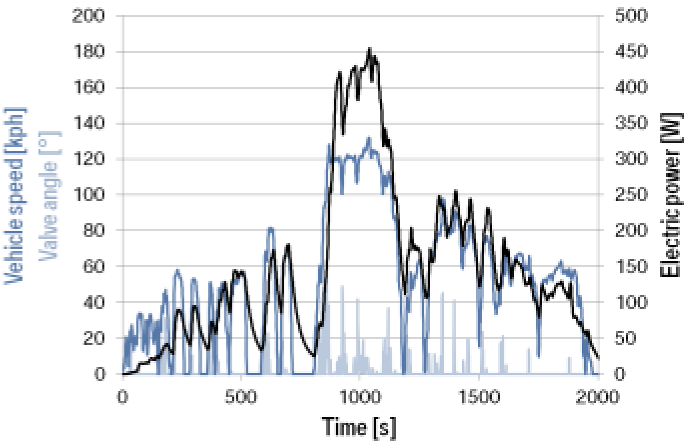
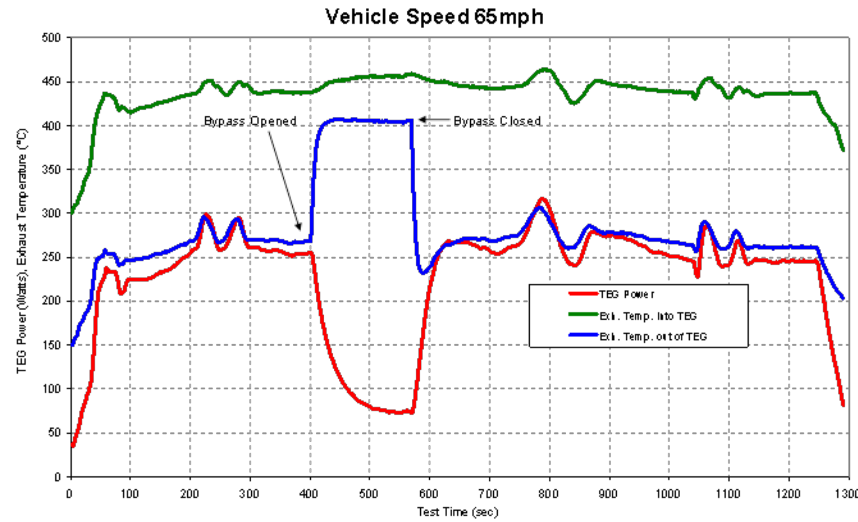
Technical Back-Up Slides

PRIOR PROGRAM - VEHICLE SUMMARY



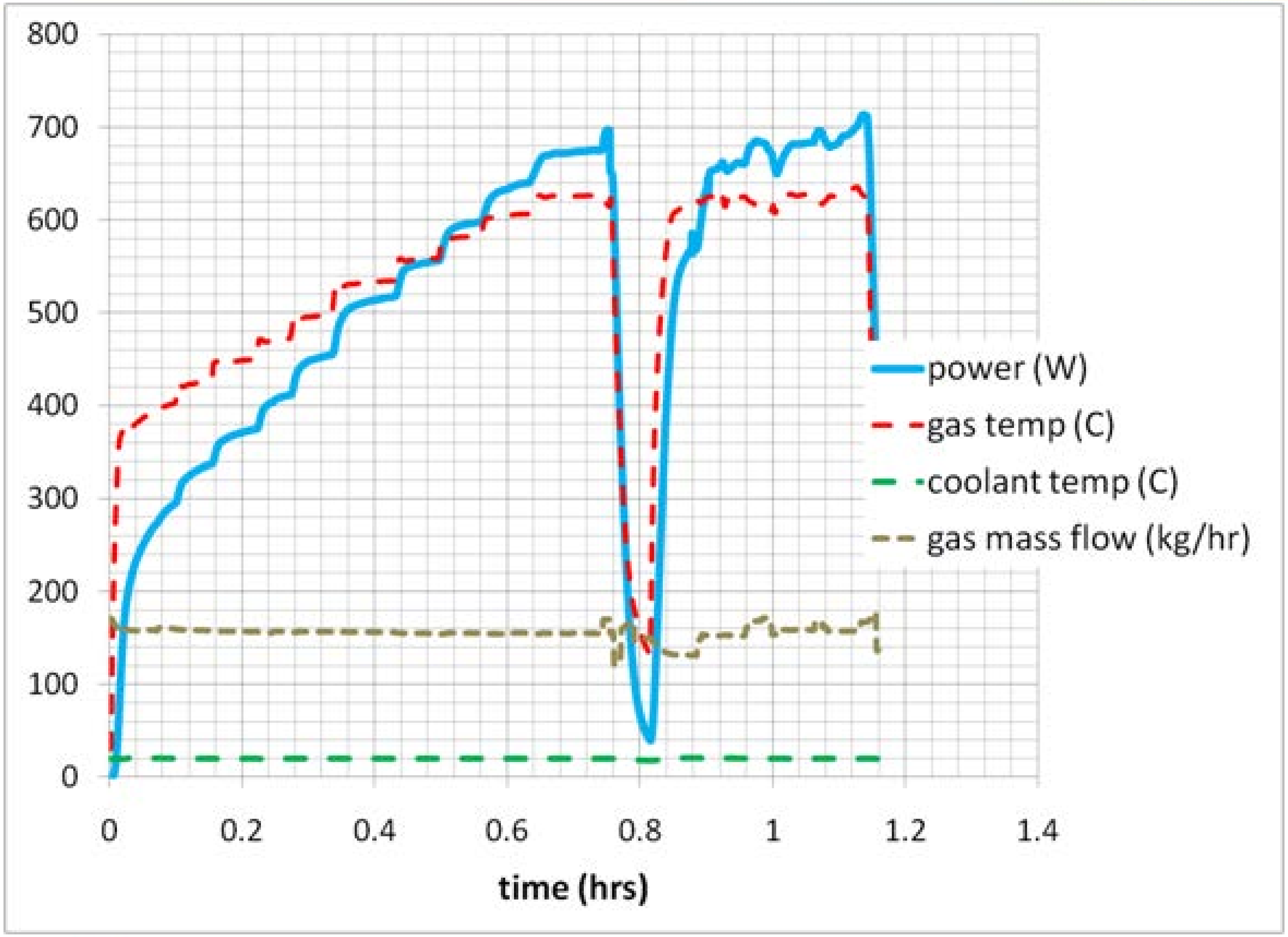


TEGs have been integrated into both BMW and Ford vehicles and have been in operation for over a year

BMW X6

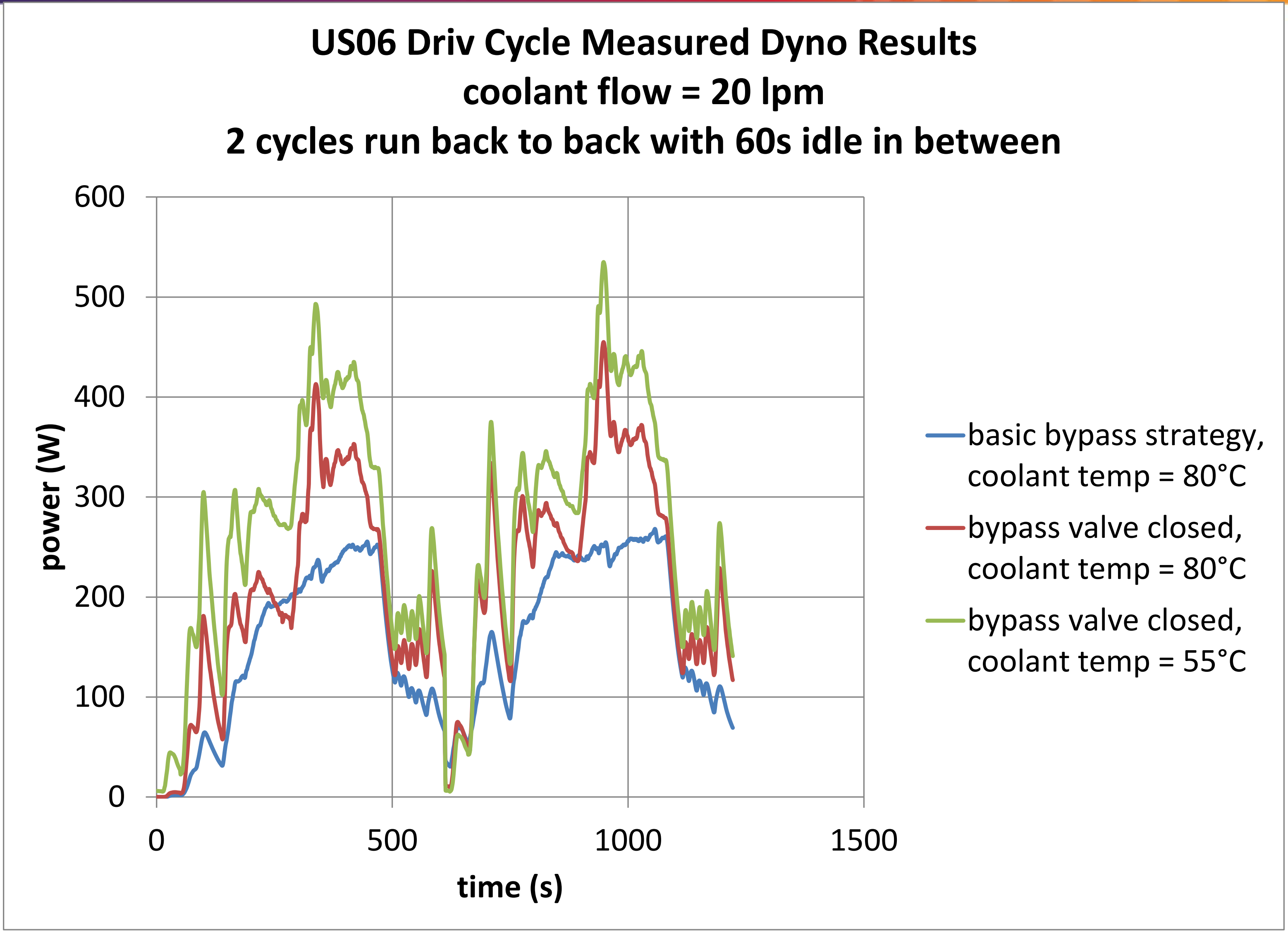
Ford Lincoln MKT

CYLINDRICAL TEG PERFORMANCE

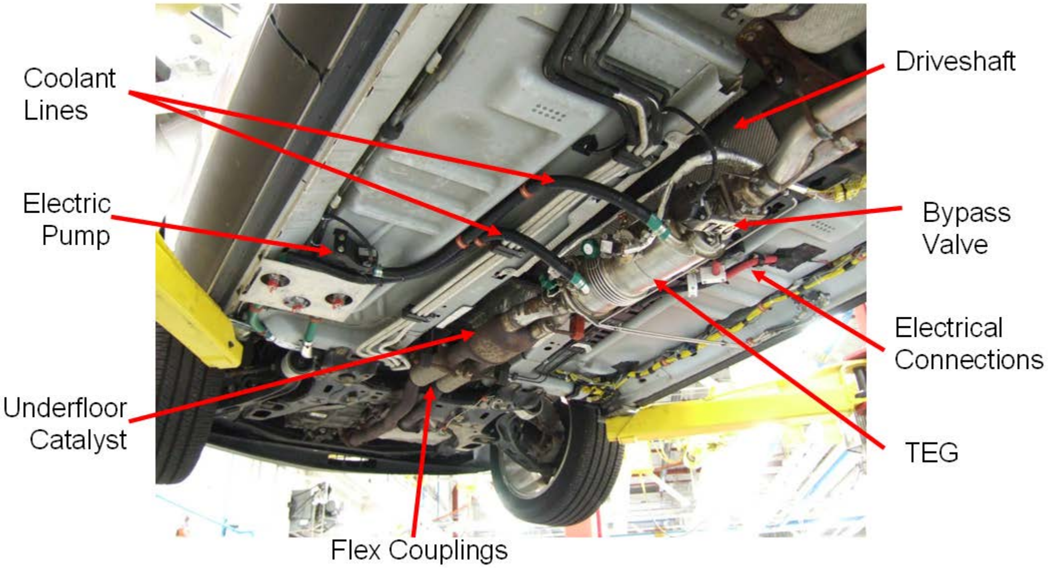


49 W/L (based on flange to flange dimension including outer shell and internal bypass)
1280 W/kg of TE material used

ENGINE DYNAMOMETER US06 DRIVE CYCLE RESULTS



VEHICLE INTEGRATIONS



TEG PERFORMANCE REPEATABILITY